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INVESTIGATION OF HIGH POWER MHD GAS LASERS

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13. ABSTRACT

This report presents the results obtained during the first half of the year 1974 in the study of MHD powered gas lasers. Key results of the work thus far are:

1. Changes to the shock tunnel and test facility include a modified cesium seed injection system, relocation of the secondary diaphragm, installation of a primary double diaphragm and a new CO_2 probe laser.

2. Gain measurements previously reported have been repeated, with substantial improvement in the signal attributable to the above changes.

3. Achievement of 19% enthalpy extraction in the MHD generator channel is an important step forward in generator performance.

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INVESTIGATION OF HIGH POWER MHD GAS LASERS

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FOREWARD

The work discussed herein is being performed at the General Electric Company, Space Division, Space Sciences Laboratory, King of Prussia, Pennsylvania, under the auspices of the Office of Naval Research and the Defense Advanced Research Projects Agency. Mr. J. Satkowski of ONR and Mr. J. Meson of DARPA are the technical monitors.

The studies presented cover the period from January 1974 to August 1974 and represent an interim report of an ongoing project.

Dr. Bert Zauderer is the principal investigator. Mr. E. Tate is responsible for the operation and diagnostic evaluation of the facility. Messrs. W. Frey, F. McMenamin, and G. Fecik provide technical assistance in the operation of the facility. Mr. D. DeDominicis was responsible for the design of the new components for the facility. Dr. C. H. Marston contributes to the analyses and evaluation of the test results.

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2. Gain measurements previously reported have been repeated, with substantial improvement in the signal attributable to the above changes.

3. Achievement of 19% enthalpy extraction in the MHD generator channel is an important step forward in generator performance.

II. PUBLICATIONS OF THE PAST 6 MONTHS

1. B. Zauderer, E. Tate, C. H. Marston, "Electrode Studies and Recent Results of Non-Equilibrium MHD Generator Experiments," GE TIS Report 74SD217.

2. E. Tate, C. Marston, B. Zauderer, "Large Enthalpy Extraction Experiments in a Non-Equilibrium MHD Generator", GE TIS Report 74SD226. (To be published in Applied Physics Letters).

3. B. Zauderer, "Closed Cycle MHD Potential Impressive", Electrical World, March 15, 1974.

4. B. Zauderer, E. Tate, and C. H. Marston, "Electrode Studies and Recent Results of Nonequilibrium Generator Experiments", 14th Symposium on Engineering Aspects of MHD, University Tennessee Space Institute, April 1974.

5. B. Zauderer, E. Tate, and C. H. Marston, "CO_2 MHD Laser, Analysis, Design and Shock Tunnel Experiments", 14th Symposium on Engineering Aspects of MHD, University of Tennessess Space Institute, April 1974.

III. CONTRACT EFFORT AND RESULTS

1. Introduction

This program is directed towards the utilization of a shock-tunnel driven supersonic channel to perform a study of gases suitable for MHD laser operation. Under the previous contract[1] MHD laser gain exceeding 0.2%/cm has been achieved in the GE/ONR shock tunnel using a mixture of 78% Helium, 18% Argon and 4% CO_2 plus 0.1% Cs seeding and a 70 He/29 Ne/1 Xe 4% CO_2 mixture. Long relaxation times and non-emitting electrodes required use of some external voltage augmentation to achieve the necessary plasma conditions in the available generator length. The results were also reported to the 14th Symposium on Engineering Aspects of MHD (1974) and the paper is included as Appendix A.

This gain measurement represents the first step in the achievement of an MHD laser, in which thermal energy is converted to optical energy in a single, static, channel at efficiencies potentially much greater than those possible in a gas dynamic laser. In a CO_2 gas dynamic laser, for example, the energy source is vibrationally excited nitrogen and this, combined with CO_2 quantum efficiency places an upper bound on overall conversion of about 4%. The MHD laser on the other hand has an upper bound of about 10%, which represents the combination of MHD generator enthalpy extraction (thermal to electric conversion) and electric discharge laser efficiency.

The MHD laser channel has a long (11"), narrow (0.125") throat through which the gas, brought to a suitable temperature and pressure by shock compression, flows into an expansion region where it is accelerated to a high Mach number ($\approx$4.5 in the case of CO_2). MHD laser operation depends on the ability to produce non-equilibrium ionization and non-equilibrium molecular vibration in a gas mixture. Free electrons at a temperature well above the static gas temperature are then the source of electrical conductivity and of energy for pumping the molecular species. A noble gas or mixture of noble gases is the major constituent, with a small amount ($\sim$0.1%) of easily ionized alkali metal to supply electrons and a sufficient quantity of the molecular gas (a few %) to supply the optical output without destroying the non-equilibrium electrical conductivity.

Of primary importance to MHD laser operation is the efficiency with which the thermal energy of the reservoir gas (in this case the gas in the reflected shock region) is converted to electrical power (enthalpy extraction). The GE/ONR shock-tunnel facility is also used to study MHD generator channels. Recently, 19.3% enthalpy extraction from a non-equilibrium plasma was obtained (the best obtained in an open cycle combustion generator 100 times larger has been 8%). The details of this work are given in Appendix B. While operating the generator channel, the diagnostic equipment for the laser channel was extensively revised, mechanical changes were made to the channel and a mirror system to obtain laser output was designed (fabrication is nearly complete). The foregoing and other experimental revisions will be described in the following sections. The laser channel is presently in operation and the latest results will be given.

2. Experimental Revisions and Additions

(a) Carbon monoxide nozzle

A nozzle for operation with carbon monoxide has been designed and fabricated. Carbon monoxide requires a lower gas temperature for lasing. The slit height is consequently .025" to give a more rapid expansion than the CO_2 nozzle. The method of characteristics was used to design a sharp edge nozzle for expanding the flow to M=8, which corresponds to a static temperature of $2000^{o}K$.

As detailed in Reference 1, deflection of the nozzle block designed for use with CO_2 caused an intolerable perturbation of the flow until additional external support was added. The smaller throat height of the CO nozzle means that slight changes in the throat height are even more critical. For this reason, the nozzle has been designed as a single assembly with a center support which will be inserted into the channel through the stagnation region. Figure 1 is a photograph of the CO nozzle.

(b) Cesium Injection System

The experimental observation that electrode conduction is enhanced by the presence of large (>1%) concentrations of cesium provided the necessary impetus for a complete redesign of the cesium injection system. This new system was a factor contributing to the achievement of 19.3% enthalpy extraction and it will be utilized for future laser channel experiments.

(c) Secondary Diaphragm Relocation

The desire to precoat the electrodes with cesium immediately prior to an experiment necessitated a relocation of the downstream diaphragm from the front of the MHD generator channel to the rear. This made possible the location of the cesium injection port at the rear of the channel with a nozzle pointing upstream so that the cesium particles would flow over the electrodes. This precoating was also a factor contributing to the 19.3% enthalpy extraction. A side benefit was that the flow started much quicker, as shown by pressures and current measurements. Success with the downstream diaphragm on the MHD generator channel encouraged a trial of the same technique on the laser channel even though its much smaller throat raised some doubt as to whether the flow would start properly. The rear of the laser channel was machined to accept a specially fabricated diaphragm holder. Changing this diaphragm conveniently had been made possible by mounting the dump-tank on tracks and using hydraulic cylinders to move it back and forth.

(d) Primary Double-Diaphragm

Since the laser channel was last operated, a double diaphragm arrangement at the shock-tunnel driver end has been installed. The two diaphragms are separated by a six inch long intermediate chamber which is pressurized. The driver-tube is then pressurized to the exact pressure desired. The intermediate chamber is then evacuated and both diaphragms immediately burst. This gives precise control over the burst pressure (and hence shock Mach number) and time of burst, which is required for optimum cesium seeding.

(e) New Wire Electrode Plates

Experiments with the laser channel and results with the generator channel have shown the desirability of using wire electrodes mounted parallel to the magnetic field. Fibreglas -epoxy plates with electrodes of this type have been fabricated and one of these plates is shown in Figure 2.

(f) Gain Diagnostics

A source of inaccuracy in the gain measurements has been the stability (both mechanical and electrical) of the probe laser. A new Sylvania 3 watt CO_2 laser was received. However, this laser had unacceptable 120 cycle ripple on its output. Since its delivery, two more power supplies were requested from Sylvania and the third power supply met the requirement of $<0.2\%$ short term amplitude stability. This laser is also inherently mechanically more stable as it is three times shorter than the laser previously used. The output stability of this laser has made possible tracking down and eliminating vibration sensitivity in all the other components of the gain measurement optical system. A total gain of 1% can now be measured with a signal to noise ratio of < 1. Further refinements of the gain measurements are expected when a pyroelectric detector (flat response at 10.6 microns) and a Hg-Cd: Te detector (greater sensitivity than Au-Ge at 10.6 microns) are used.

(g) Optical Resonator

An investigation of laser resonator configurations was completed. A spherical 99.5% reflecting mirror and a flat 98% reflecting output coupler was chosen as the resonator configuration offering the best compromise between enclosed mode volume and alignment tolerance. The mirror and coupler will be mounted outside the channel and Brewster angle windows will be mounted on the channel. All optical components (except for the concave mirror which is a dielectric coated copper mirror) are made of zinc selenide. Zn Se has several advantages over other materials for use in the infra-red but the primary reason for its use is that it is transparent to visible radiation. This will facilitate alignment and a He-Ne laser will be used for alignment. All the optical components are on hand. As it is expected that mechanical vibration of the optical components will be the major difficulty in getting laser power extraction, a massive aluminum table has been fabricated and the optical components are presently being mounted on it.

3. Gain Measurements

Following the improvements in the gain diagnostics and the relocation of the secondary diaphragm more gain measurements have been made. A series of experiments were performed with the diaphragm switched from front to rear on alternate runs. The results of these experiments are shown in Figure 3. Figure 3(a) and 3(b) show detector outputs for front diaphragm and rear diaphragm experiments, respectively. The gas mixture was 50% Argon/ 50% Helium to give a molecular weight of 22 to simulate the normal GDL mixture of 48% N_2/40% He/12% CO_2. A comparison of 3(a) and 3(b) shows that the initial several milliseconds of absorption is almost certainly beam bending due to a very disturbed flow caused by aluminum pieces obstructing the throat. The high frequency spikes are also absent in 3(b) and these were, therefore, (as suspected all along) a result of aluminum particles interrupting the probe beam. Figure 3(c) and 3(d) are a similar comparison for a mixture containing CO_2 (48% N_2/40% He/12% CO_2). Figure 3(c) is a gain measurement typical of all those reported previously (although with a considerably improved signal to noise ratio) and was made with a front diaphragm location. Figure 3(d) is a detector signal with the diaphragm at the rear. The signal rises quickly ($\approx$400 μsec) to its peak value and then decays slowly with time back to the base line. The initial several milliseconds absorption and the high frequency transients are absent. There is still a small initial beam bending as the shock front passes the windows. The second "absorption" is caused by the reflected shock from the rear diaphragm. This shock is clearly observed by pressure transducers. A typical pressure transducer trace is shown in Figure 4. A reflected shock was also present in the MHD generator experiments when a rear diaphragm was used. The vertical scale for Figure 3 (all oscillograms) is 50 mv/cm and the total detector output varied between 0.5 and 1.0 volts. One centimeter deflection on 3(d) represents 10% gain. Figure 5 is the detector output for an experiment in which the probe laser was off and the detector gave zero output so no spurious infra-red radiation was present. These measurements indicate that the gain diagnostic procedure is accurate. The next step will be to do these measurements with currents and magnetic field applied to He/Ne/Xe + CO_2 and He/Ar /Cs + CO_2 plasmas to see if such accurate measurements can be done in the presence of electromagnetic interference. Further confirmation of the measurements will be made when the optical resonator is installed to extract laser power. The above measurements show that the facility can be accurately employed (with appropriate channel throats and suitable probe laser) for investigation of other potential lasing media.

IV. REFERENCES

1. B. Zauderer, E. Tate, and C. H. Marston, "Investigation of High Power MHD Gas Lasers", General Electric Co., Contract No. N00014-73-C-0243, 1973.

FIGURE 1 Mach 8 sharp edge nozzle for use with CO

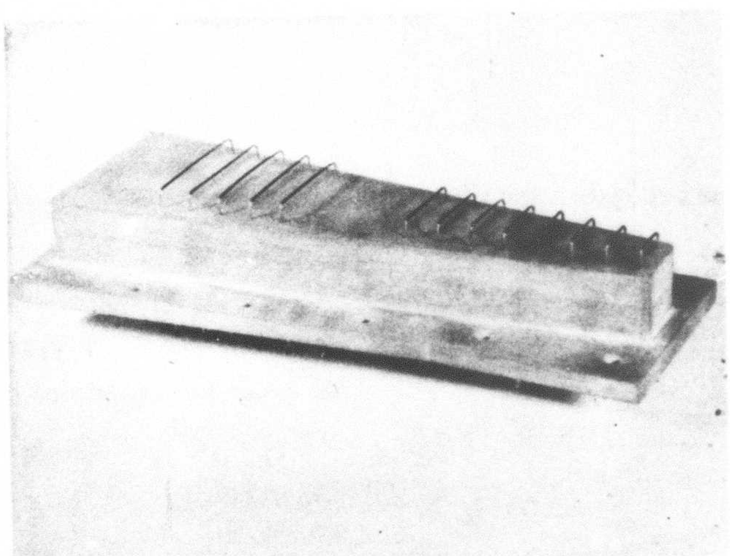
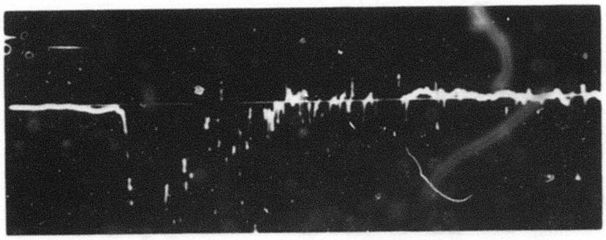
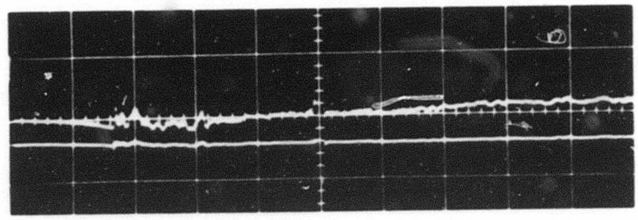


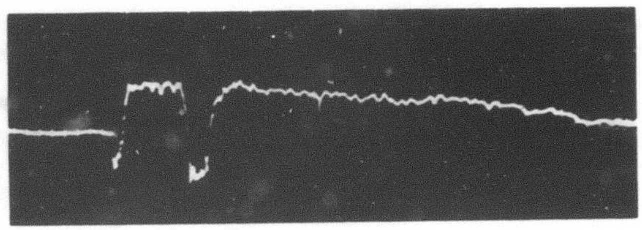
FIGURE 2 A wire electrode plate.





(a) front diaphragm - no CO_2

(b) rear diaphragm - no CO_2 (Upper trace)



(c) front diaphragm - with CO_2

(d) rear diaphragm - with CO_2

All oscillograms 2 ms/cm horizontal axis

All oscillograms 50 mV/cm vertical axis - D. C. level 500 →1000 mV

A vertical deflection indicates gain.

FIGURE 3 Detector outputs for front and rear diaphragm experiments

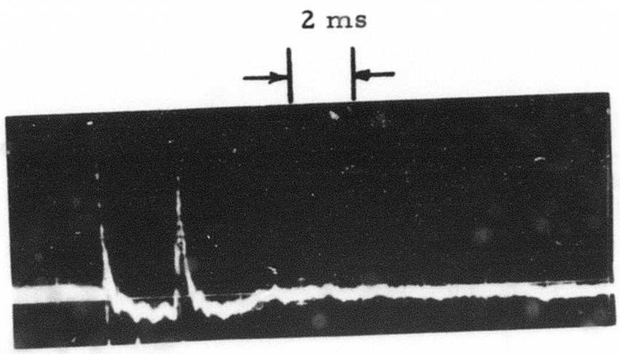


FIGURE 4 Pressure measurement showing initial and reflected shocks in MHD laser channel

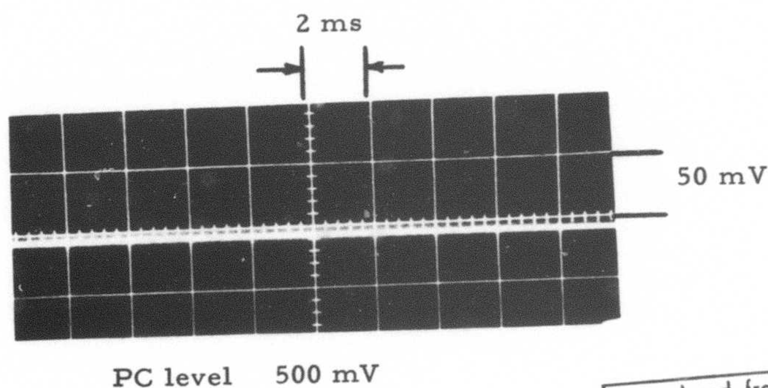


FIGURE 5 Detector output with probe laser off

APPENDIX A

14th SYMPOSIUM ON ENGINEERING ASPECTS OF MHD (1974)

CO_2 MHD LASER; ANALYSIS, DESIGN AND SHOCK TUNNEL EXPERIMENTS

B. Zauderer, E. Tate and C. H. Marston
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King of Prussia, Pa.

Abstract

MHD laser gain exceeding 0.2%/cm has been achieved in the GE/ONR shock tunnel using a mixture of 78% Helium, 18% Argon and 4% CO_2 with either 1% Xe or 0.1% Cs added to the basic mixture for seeding. Long relaxation times and non-emitting electrodes required use of some external voltage augmentation to achieve the necessary plasma conditions in the available generator length. The MHD laser analysis, design of a channel based on that analysis, and experimental results to date will be discussed.

CO_2 was chosen as the laser medium because it has a reasonably high quantum efficiency (~ 41%), requires pumping to energy levels comparable to expected electron energy in an MHD generator (a few tenths of an electron volt) and is reasonably well understood as a result of the large effort which has been directed toward development of both gas dynamic and electric discharge lasers.

I. Introduction

Successful operation of an MHD laser requires satisfactory resolution of a number of conflicting requirements. To cite a few examples: the presence of a molecular species, such as CO_2, tends to degrade generator performance, thus, the concentration of the laser medium must be kept as low as practical, consistent with the absolute concentration required to achieve laser gain; static temperature must be low enough to avoid equilibrium thermal population of the lower laser level yet stagnation temperature must be sufficient to meet energy flux requirements; cesium seed can react chemically with CO_2 and CO_2 may lower electron temperature by quenching excited Cs atoms. The absolute electron concentration must be sufficient for adequate current density yet low enough to avoid exciting a large fraction of the CO_2 molecules to the lower laser level. These and other conflicts were resolved in the design and operation of a special laser channel in the GE/ONR shock tunnel facility.

II. Analysis and Design

A fairly simple model was formulated to describe the MHD laser and gas dynamic flow conditions in order to establish bounds on the pertinent parameters and achieve sufficient understanding of the situation to design an effective channel.

Effective electrical conductivity, assuming a Faraday channel and including the effect of plasma turbulence was taken as

$$\sigma_{eff} = 2\sigma/\beta_e \tag{1}$$

Where β_e is the Hall parameter ($\beta_e \geq 2$). The electron energy equation[1], modified by an inelastic collision loss factor δ_{eff} can be written for a one-dimensional perfect gas compressible flow in a short circuited channel as

$$\frac{3}{2}\,\delta_{eff}\left[{}^{T_e}/_{T_g} - 1\right] = \gamma M^2 \beta_e \tag{2}$$

where T_e and T_g are electron and gas temperatures, γ is the specific heat and M the Mach number. A weighted average δ_{eff} was calculated from data for cross-sections[2] and inelastic losses[3]

$$\delta_{eff} = \left(\frac{\Sigma_j\, \delta_j\, X_j\, Qej/Mj}{\sum_j Xj \;\; Qej}\right)\left(\sum_j XjMj\right) \tag{3}$$

For reasonable assumptions concerning stagnation temperatures, electron temperatures, and static gas temperatures, a design Mach Number of 4.5 and a CO_2 concentration $\leq 5\%$ were established with the aid of equations 1 - 3. Gas pressure was initially specified assuming a Hall parameter limited to ~ 10 by ion slip, and a magnetic field of 2.5 Tesla.

The electron density range within which a population inversion can be achieved was estimated by considering the rates of excitation and deexcitation of the appropriate laser levels by collision with electrons and with helium atoms.[4] The electron rate constants of Bell and Bradley were used in the original analysis but those of Nighan and Brown[5] give similar results. A range of 10^{12} to 5×10^{12} was estimated, neglecting the effect of laser power output. This estimate is also consistent with the results of Nighan and Brown.

A source of concern in MHD laser operation is quenching of cesium resonance radiation by molecular species since this will have the effect of lowering electron temperature and reducing electrical conductivity. Mnatasakanyan[6] showed that a large increase in δ_{eff} for Nitrogen which resulted from the addition of cesium to a nitrogen argon mixture, could be attributed to quenching. Also, reaction of cesium and CO_2 to form CO and cesium oxides must be considered. These effects can be minimized by keeping the cesium concentration as low as possible and in any event much less than the CO_2 concentration.

Nozzle design and channel were established so as to minimize length of channel needed for re-

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laxation to non-equilibrium steady state and for sufficient MHD interaction.

A sharp cornered nozzle was used. The nozzle section is a removable steel insert approximately 2 1/2 inches in the flow direction. Most of the expansion takes place in this section although there is also some divergence built into the fiber-glas-epoxy MHD channel. Since the channel is relatively broad in the y direction and shallow in the z direction, a pair of Helmholtz coils were used to provide the magnetic field.

III. Experimental Set-up

The channel and magnet assembly are shown in Fig. 1 as they looked prior to completion of external electrode wiring and connection of the magnet to its capacitor bank power supply. Electrodes are segmented in both the x and y directions and consisted initially of 19 rows of flush mounted tungsten cylinders with up to 11 electrodes in each row. To reduce electrode loss, each electrode was later drilled to accept a short protruding tungsten pin.

Instrumentation for small signal gain measurement is shown in Fig. 2. A single mode beam from a small CO_2 probe laser was directed through germanium windows approximately 13 cm from the nozzle exit. Two gold-doped germanium detectors and a beam splitter mirror permitted continuous monitoring of the laser output during a run. A considerable effort was necessary to:

- Isolate detectors and probe laser from shock induced mechanical vibration.
- Modify the laser power supply to achieve 1% short term amplitude stability with single mode operation.
- Eliminate electromagnetic interference by the use of multiple shields for the detectors combined with careful grounding of all circuitry.

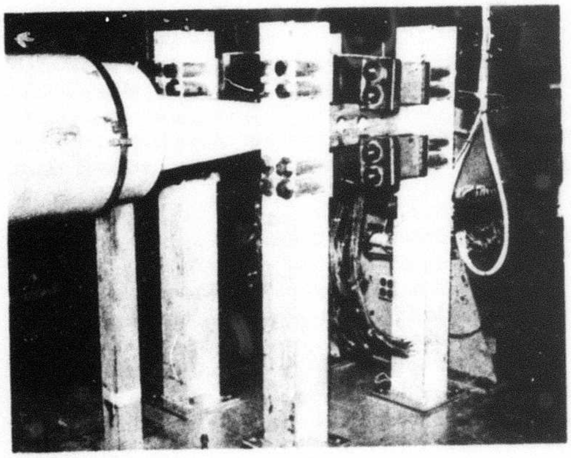

Fig. 1. Photograph of the Assembled MHD Laser Channel and Magnet. The View is in the Upstream Direction Toward the Shock Tube.

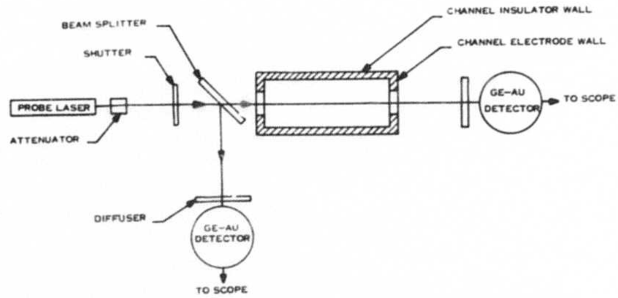

Fig. 2. Instrumentation for Laser Gain Measurements.

Fig. 3 shows the detector signal after completion of these modifications.

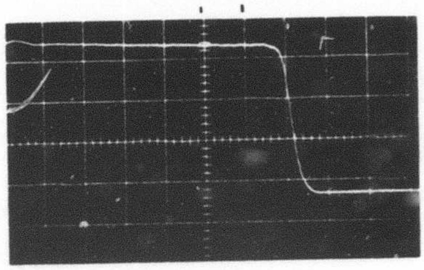

Fig. 3. Detector Signal With No CO_2 in Test Gas. Effect of Shock Wave Can Be Seen at Extreme Left. Mechanical Shutter Cuts Off Signal at About 30 ms.

IV. Gas Dynamic Laser Measurements

Gas dynamic laser gain tests were performed to check out the CO_2 laser gain equipment without the complication of interference from electrical and magnetic fields and to establish the gas dynamic operating characteristics of the channel.

The GDL mixture selected was 12% CO_2 + 48% N_2 + 40% He at 12 atm. and 1500° K stagnation conditions. Numerical analyses of the supersonic expansion indicated that the small signal gain should be about 0.2%/cm at the viewing port in the channel, but in the initial experiments only absorption was observed during the 2 ms test time except for a small initial spike. This measurement plus high static pressure in the channel led to the suspicion that the channel walls and the nozzle were being spread apart during the test time by the gas stagnation pressure. Direct measurement showed that nozzle flexing during the first two milliseconds of the test time was large enough (about 50% of the throat height) to reduce the gain to zero.

After strengthening the nozzle and extending the test time to 14 milliseconds by using a sphere at the end of the driver, more GDL experiments done, Fig. 4. The longer test-time still gave absorption for about 6 milliseconds but then gain was

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observed, thus providing the desired checkout of the diagnostics.

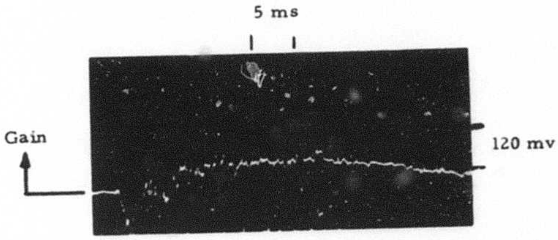


Fig. 4. Gas Dynamic Laser Gain With Reinforced Nozzle and With Sphere to Extend Test Time to 14 ms.

V. MHD Laser Measurements

A variety of mixtures were run in preliminary MHD laser experiments, Table I, but the two that yielded reproducible gain measurements were:

. 78%, He, 18% Ar, 4% CO_2 with 0. 1% Cs seed added

. 68% He, 27% Ne, 4% CO_2, 1% Xe

The use of Xe as a source of electrons eliminated the chemical reaction and possible quenching effects associated with cesium and enabled us to show experimentally that with a 4% mole fraction of CO_2 (sufficient for a concentration of 10^{16} cm^{-3}) laser gain was feasible. Once that was achieved, we returned to cesium seed to improve MHD performance and found that seed levels of 0. 1% cesium were effective.

Quenching was not a serious problem but most of the cesium reacted with the CO_2 to form cesium oxides prior to firing the shock tunnel. A light scattering measurement showed that concentration of cesium aerosol dropped by a factor of 5 to 7 when CO_2 was present in the gas mixture. Products of the reaction are not certain, but on the assumption that they are primarily CO and Cs_2O, the reaction is weakly exothermic at room temperature(7). Subsequent shock heating decomposed the oxide and, as evidenced by a current density of about . 3 a/cm^2, sufficient free electrons were available. From this we conclude that in gas containing both CO_2 and cesium the CO_2 mole fraction must be much larger than the cesium mole fraction so that most of the CO_2 will remain unreacted.

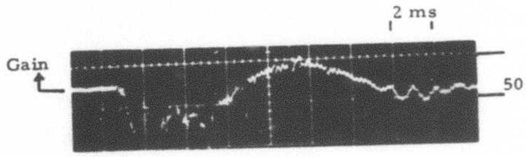
The computer code developed for MHD generator analysis(8) which uses the Shkarovsky-Lau conductivity model(9) was modified to include CO_2 as a constituent of the plasma. Vibrational interaction was accounted for in an approximate way by considering the energy difference and rate[5] for interaction of free electrons with the CO_2 010 vibrational level. While this does not give us a prediction of the CO_2 vibrational inversion, it did provide an estimate, Table II, of the gas dynamic and MHD conditions at which gain was measured.

Voltage augmentation was required to maintain electrode conduction. Due to the short axial length of the channel, external voltage augmentation was used to obtain required ionization buildup. As has been explained elsewhere(10), a discharge transverse to a gas flow is subject to extinction by gas convective effects in the ionization relaxation region. Thus, a voltage which is considerably greater than the discharge sustaining voltage must be applied across the electrodes in the channel. The use of non-emitting electrodes in this experiment further increased the ratio of ignition voltage to sustaining voltage.

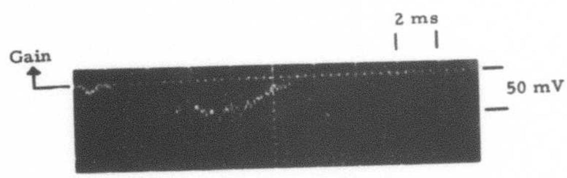
Once the discharge was ignited, all but 100 volts of the augmentation voltage appeared across the external load resistors. Improvements in the electrode configuration and/or surface treatments are expected to permit operation of the generator at large CO_2 concentrations without any external supplement to the internally developed generator voltage.

Also of interest is the very high value of $\omega\tau$ ($\omega\tau$ = 39) at which the MHD channel was successfully operated. Most non-equilibrium MHD generators operate in $\omega\tau$ range of 1 to 10.

Figure 5 shows measured gain. Note that it takes approximately 8 milliseconds to establish the flow. Total test time is about 14 ms but stagnation pressure is dropping near the end of that time so the gain tends to decrease. The relatively long test time is a result of the very small throat size required to give sufficient expansion for proper MHD laser flow conditions. Test time is limited by arrival of expansion waves from the driver end of the tube rather than by drain time, even though a sphere is used at the end of the driver to delay propagation of the expansion waves.



10. 6 micron Small Signal Gain with CO_2



10. 6 micron Signal without CO_2

Fig. 5. 10. 6 Micron Signal With and Without CO_2

Table I. Table of Various Gas Mixtures Tested in The MHD Laser Channel

Test Gas	% C_s	% CO_2	% N_2	% Gain	Comments
81% He/19% Ar	1.0	All Conditions		0	$n_{C_s} \approx n_{CO_2}$ Hence No Gain
↓	0.1	2.3	0	0	n_{CO_2} Too Small
↓	0.1	2.5	2.5	0	n_{CO_2} Too Small
↓	0.1	3.9	0	4→9	n_{CO_2} Sufficient for Gain
↓	0.1	0	0	0	NO CO_2 Hence No Gain
70% He/19% Ne/1% Xe	0	0.25	0	0	n_{CO_2} Too Small
↓	0	0.50	0	0	n_{CO_2} Too Small
↓	0	2.00	0	0	n_{CO_2} Too Small
↓	0	0.50	0.50	0	n_{CO_2} Too Small
↓	0	1.80	1.80	0	n_{CO_2} Too Small
↓	0	1.70	0	0	n_{CO_2} Too Small
↓	0	3.80	0	≈ 6	n_{CO_2} Sufficient For Gain
↓	0	4.10	0	≈ 6	n_{CO_2} Sufficient For Gain
↓	0	0	0	0	NO CO_2 Hence No Gain

Table II. MHD Laser Operating Conditions

Mixture: 78% He, 18% Ar, 4% CO_2, 0.1% Cs

Gas Dynamic Conditions:
$M = 5$ $\quad u = 2370$ m/sec
$T_o = 1880^\circ K$ $\quad T_{static} = 196^\circ K$
$p_o = 3.4$ atm $\quad p_{static} = 6.9$ torr

MHD Conditions:
$B = 1.66$ tesla
$j = 0.29$ a/cm^2
$V_{ext} = 1800$ V, $R_{ext} = 1000\ \Omega$, $I = 1.7$a
$V_{net} = 100$ V (Net Augmentation)
$uBy = 1080$V (Induced Internally)

Calculated Properties*:
$n_e = 5.8 \times 10^{12}$ cm^{-3} $\quad n_{CO_2} = 1.0 \times 10^{16}$ cm^{-3}
$T_e = 2085^\circ K$
$\omega\tau = 39$
$\sigma_{eff} = 1.6$ mho/m

* Shkarofsky-Lau Conductivity Model Plus CO_2 - 010 Vibration Energy

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VI. Conclusion

Achievement of laser gain in an MHD channel with external voltage augmentation is the first step toward the development of a device capable of transforming thermal energy to coherent optical energy in a single gas dynamic channel. The test condition provides a bench mark from which to work for further improvements in electrode configuration, magnetic field and other variables to reduce the required external augmentation to a preionizer section or eliminate it altogether.

VII. Acknowledgements

The authors wish to thank Mr. L. D. DeDominicis for his contributions to the design of the channel and magnet assembly and Messrs. W. Frey and F. McMenamin for their assistance in performing the experiments. This work was supported in part by the Defense Advanced Research Projects Agency and by the Office of Naval Research.

VIII. References

1. H. Hurwitz, Jr., G. W. Sutton and S. Tamor, ARS Journal Vol. 32, pp. 1237-1243 (August 1962).
2. S. T. Demetriades, G. Fonda-Bonardi, and G. S. Argyropolous, AFOSR Technical Report 69-2809, September 1969.
3. H. Massey and J. D. Craggs, in Handbuch der Physik Vol. 37/1, pp. 314 (Springer-Verlag Berlin, 1959).
4. J. C. Bell and D. Bradley, in Combustion and Flame, Vol. 14, pp. 225-236 (1970).
5. W. L. Nighan and R. T. Brown, "Laser Excitation Using a Non-Equilibrium MHD Generator", AIAA Paper 71-67 (1971).
6. A. Kh. Mnatsakanyan, "Electron Energy Balance in a Plasma with Molecular Impurities", High Temperature (Translation from Russian) 8, 1079-1083 (1970).
7. M. Linevsky, Private Communication.
8. B. Zauderer and E. Tate, "Experiments in a Large Non-Equilibrium MHD Generator with Cesium Seeded, Noble Gases", in 5th International MHD Power Generation Conference (ZAED, Karlsruhe, 1971), Vol. II, pp. 431-446.
9. J. Lau, "Electrical Conductivity of Inert Gases Gases - Seed Combination In Shock Tubes", Can. J. Physics, 42, 1548, (1964).
10. B. Zauderer, "Discharge Structure and Stability of a Non-Equilibrium Plasma in a Magnetohydrodynamic Channel", Physics of Fluids, 11, 2577-2585 (1968).

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APPENDIX B

APPLIED PHYSICS LETTERS (To be published)

LARGE ENTHALPY EXTRACTION EXPERIMENTS IN A NON-EQUILIBRIUM MAGNETOHYDRODYNAMIC GENERATOR

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A measure of the performance of a magnetohydrodynamic generator is the enthalpy extraction (power out/heat in) which generally must exceed 20% to operate efficiently in a thermodynamic Brayton power cycle. For the first time 1.82 megawatts, which represented 19.3% enthalpy extraction, was achieved in a non- equilibrium plasma, magnetohydrodynamic generator. Cold electrodes were used. Theoretical calculations show that 30% enthalpy extraction could be achieved with thermionically emitting electrodes.

Enthalpy extraction (electrical output/thermal input) of 20% is generally accepted as the minimum needed for successful development of Magnetohydrodynamic (MHD) generators. This is true of both the closed cycle (non-equilibrium, noble gas) and open cycle (combustion gas) types,[1, 2] although recent calculations[3] indicate that, in open cycle systems a somewhat lower value is acceptable if the combustion air can be preheated to 3000°F in a heat exchanger directly fired by the corrosive MHD generator exhaust.

An enthalpy extraction of 19.3% has recently been achieved in a shock-tunnel driven magnetohydrodynamic (MHD) Faraday generator. This was done by utilizing the non-equilibrium ionization concept in which Joule heating preferentially excites the plasma electrons so that their density is characteristic of a temperature higher than the gas temperature as a whole. The test gas was neon seeded with cesium.

A one foot diameter, sixty foot long shock tunnel was used to process the test gas to pressures of 4 - 5 atmospheres and temperatures of 3000 - 3500°K. The gas flowed through a convergent - divergent nozzle before entering the generator (see Figure 1). The gas traversed the generator in 400 microseconds and as the total test time was 10 milliseconds, the flow thus reached steady state conditions.

The MHD generator has entrance dimensions of 10.3 x 7.8 cm. and exit dimensions of 25.4 x 19.1 cm. to give an area ratio of 6 to 1.

The generator entrance was 20 cm. downstream of the throat. Previous experiments[4] had also shown that wire electrodes parallel to the magnetic field and mounted away from the electrode walls resulted in lower electrode losses (than flush mounted electrodes) and did not disturb the supersonic flow in a drastic manner. The electrodes were 40 mil tungsten wires protruding 0.5 cm. from the electrode walls. There were 74 pairs of electrodes with the last dozen locations having two pairs at each axial location.

The magnet was of saddle-coil construction. To maximize the peak field, within the constraint of 1 megajoule available from the capacitor bank power supply, the windings were diverged in two directions with the same angular divergences as the generator walls. The rise time (quarter cycle) was 4 milliseconds, the magnet being crow-barred at the quarter cycle point at which time the test gas entered the MHD generator.

Seed was introduced by flowing cold test gas over a hot bath of cesium. Particles of order 1 micron diameter were entrained and the mixture was then introduced into the shock-tube. After loading the shock-tube, the test had to be completed within one minute, otherwise the larger cesium particles fell, to the bottom of the shock tube.

A double diaphragm driver arrangement provided the precise timing control necessary. The cesium injection system was designed to supply a greater concentration of cesium than necessary for plasma conductivity enhancement as previous experience had shown that large concentrations ($\approx 1\%$) of cesium enhanced electrode conduction. Changes (from previous experiments) made to enhance electrode conduction were to relocate the cesium injection system to the rear of the MHD generator. This provided a cesium flow directly over the electrodes, thus depositing a cesium layer upon them prior to the start of an experiment. A thin aluminum diaphragm separated the rear of the generator from a large vacuum dump tank.

The conditions for 19.3% enthalpy extraction were as shown in Table 1. Although the stagnation temperature was 3520°K, it should be noted that the gas static temperature (after flowing through the convergent - divergent nozzle) at the first electrode was only 2020°K and at the generator exit was only 1200°K. Previous work[5] has shown that enthalpy extraction in a non-equilibrium MHD generator is a very weak function of the gas stagnation temperature.

The theoretical analysis showed (using the experimental load resistors to determine the current) that the electron temperature rose quickly in the generator to 2700°K and fell off to 2400°K at the generator exit. This effect is strongly illustrated by the power distribution curve shown in Figure 2. The current rose quickly to a large value after several electrode pairs and reached a maximum at a distance equal to one third of the generator length. The discontinuity in power near the downstream end of the generator was caused by a change from single electrode pairs loaded with 1.7 ohms to double electrode pairs each loaded with 1.7 ohms to give, in effect, 0.85 ohms at those axial locations. The theoretical analysis predicted a net enthalpy extraction of 20% which was in good agreement with the actual output. The measured electrode drop of 150 volts was used as an input to the theoretical analysis. The theoretical analysis gave a gross enthalpy extraction (the sum of the power lost due to the 150 volt electrode loss and the power delivered to the load) of 30%. At this value strong aerodynamic loading (i.e. flow deceleration) caused choking of the flow near the generator exit. The choking was not a serious problem because lowering the power output of the generator by a small amount ($\approx$5%) removed the choking effect.

Run 424 which gave a net enthalpy extraction of 11.3% is shown (see Figure 2) for comparison with Run 182A[6]. Run 424 was made prior to the changes in experimental setup previously described but under similar conditions of pressure, temperature and magnetic field. Because the interaction was smaller, power output was uniform throughout the generator. The Mach number at the entrance of the generator was 1.5. At open circuit the exit Mach number was 3. At the 19.3% enthalpy extraction condition, the Mach number decreased in the channel and the analysis indicated it approached unity near the channel exit.

The experimentally measured enthalpy extraction varied linearly with magnetic field (see figure 3). The theoretical net extraction was in agreement with the experiment if a 150 volt loss was used above 17 kilogauss. The voltage loss was gradually decreased to 80 volts at 12 kilogauss. The theoretical gross enthalpy rose with magnetic field and then levelled off as the aerodynamic loading became strong enough to approach choking conditions. This occurred at slightly over 30% enthalpy extraction. An obvious conclusion is that, as the magnetic field is increased, a greater percentage of the gross enthalpy was delivered to the external load resistors because the voltage loss became a smaller proportion of the total voltage available. The computed turbine efficiency of this generator was 60%. Due to the electrode losses (which could of course be eliminated with thermionic emission) the net isentropic generator efficiency was 40%. At about 70% isentropic efficiency and 30% enthalpy extraction, power plant efficiencies of around 50% would be attainable.

It should be noted that these experiments indicate that 30% enthalpy extraction could be achieved in a generator with thermionically emitting electrodes. This is far better than had been thought possible and places the closed cycle MHD generator in the enthalpy extraction range accessible to turbines.

ACKNOWLEDGEMENT, FOOTNOTES, AND REFERENCES

* Sponsored in part by the Office of Naval Research and by the Defense Advanced Research Projects Agency.

1. L. E. Ring, G. W. Garrison, T. R. Brogan, and H. J. Schmidt, 13th Symposium on Engineering Aspects of MHD, Stanford University, March 1973, page V. 8. 1.
2. J. F. Louis, Office of Coal Research, R & D Report #71, U. S. Dept. of the Interior, 1972.
3. F. Hals and R. Gannon, ASME Paper 73-WA/Ener - 10, November 1973.
4. B. Zauderer, E. Tate, 12th Symposium on Engineering Aspects of MHD, Argonne National Laboratory, Argonne, Illinois, Page I. 6. 1, March 1972.
5. B. Zauderer, V. International Conference on MHD, Page 305, Munich 1971.
6. Letter A Suffix denotes new series of runs beginning April 1973.

FIGURE AND TABLE CAPTIONS

FIGURE 1	Schematic drawing of the MHD generator.
FIGURE 2	Variation of power output per electrode location versus axial electrode location.
FIGURE 3	The variation of experimental and theoretical enthalpy extractions with magnetic field.
TABLE 1	The generator conditions pertaining to the extraction of 19 percent of the thermal input power, run 182A.

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